Techniques used to construct an energy model for attaining energy efficiency in buildings

A Review

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***Abstract*—A number of techniques have been developed to construct load models or energy consumption models that simulate a building's energy system, consisting of HVAC and lighting, etc for load prediction or cost saving estimates. Such models vary in magnitude from modeling of a single slab (or a wall) to modeling of a complete building through modeling of rooms subjected to temperature variations. Different classification of building energy model development is reviewed in this paper. This paper reviews various documented research works of modeling techniques employed to develop an energy model in order to achieve the target of energy efficiency in buildings.**

Keywords—Models, Building Energy System, Lumped Capacitance Model, Model predictive control

I. INTRODUCTION

A number of methods have been developed to construct load models or energy consumption models that simulate a building / plant system for load prediction or cost saving estimates. Such models vary in magnitude from modeling of a single slab (or a wall) [1] to modeling of a complete building through modeling of rooms subjected to temperature variations. Clarke [2] gave a three stage process for model formulation. In the first step, the building system is converted from continuous state to a discrete state. This involves selection of nodes at the points under study, representing the homogeneous or non – homogeneous control volumes like that of internal air mass, boundary surfaces, building fabric elements, renewable energy systems, equipments of the room, etc. Equations satisfying mass, momentum and energy conservation principles are developed in the second step for each node which is in thermodynamic contact with its surrounding nodes. Last step involves solving the equations derived in the second step for successive time steps to obtain state variables of the node for future time periods as a function of present time state variables with the boundary conditions prevailing at both times.

Models developed to simulate the building energy systems can be divided into many types. Basically, models are classified as physical, symbolic and mental models. Symbolic models are comparatively less complex and are thus frequently used. Models can be mathematical and non-mathematical models. Development of mathematical model of a system involves mapping of the physical laws governing the dynamics of the system's process into mathematical relations using variables and constants. Due to ease in evaluation and manipulation mathematical models are the most suitable and the most widely used category of models [3]. Mathematical models can be of theoretical and experimental type. As name suggest, theoretical models involve breaking down of a larger system under study into a number of smaller and simpler subsystems. Mathematical equations constrained through physical laws are then used to relate the different subsystems. On the other hand, experimental models are developed through empirical relations i.e., through measurement of input and output signals of the system and then, evaluating the system's response. Such models don't provide any information about the mechanics or behavior of the system. Differential or difference equations along with the use of soft computing techniques like fuzzy are made use of in experimental modeling.

Models are also classified as White box, Grey box or Black box models as shown in Fig. 1.

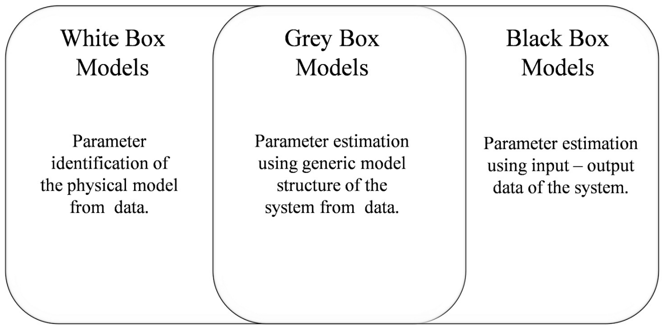

Fig. 1.Classification of models on basis of parameter identification techniques

White box modeling of buildings involve a detailed description of the heat transfer processes occurring in the building. A thorough understanding of the system and all influential sub processes is required to efficiently describe the dynamics of a building energy system [4]. Also called as semi-physical models, Grey box models are inherited from the white box models [5] but the parameters of the model defining the system are not measured directly but estimated through various identification processes [6]. Models which do not normally contain any physical knowledge regarding the system (majorly due to lack of knowledge about the physical structure of the system) are called as black box models. Statistical methods are used to formulate the model [7] and the physical parameters are partly hidden in the discrete time parameterization. Constructing an accurate and a generic model to interpret the thermal dynamics of a building involves solving heat transfer equations of conduction, convection and radiation and mass transfer equations.

The paper is structured as follows. Section II presents a comprehensive review of different models developed using Lumped Capacitance method. Reducing order of the model for simplicity using an error indicator is also illustrated. Section III presents work done in developing models in frequency domain. Section IV depicts conclusion.

II. LUMPED CAPACITANCE MODELS

Ouyang and Haghighat [24] used state space control technique for calculating thermal response factors of building envelopes. The procedure involved development of a rational transfer function using simple series expansion followed by establishing a state space equation of the system using linear interpolation and calculation of a state transition matrix. Simple series multiplication of matrices yielded the response factors for the linear time-invariant discrete systems with single input and single output. Present and past input values along with the present state of the system were related to the state at any future instant. Using time series of a triangular impulse input and that of the output functions, thermal response factors were calculated using state space principles. Developed method was implemented for calculating the thermal response factors of a five layer wall. Such a method was simple (though less accurate) and avoided the need to calculate the roots of the system transfer function and there were no miscalculations due to missing of roots.

Hudson and Underwood [10] developed a lumped capacitance model for a room with an external wall, internal floor, ceiling and partition walls in MATLAB – SIMULINK. Heat supplied by the plant, internal causal heat gain, solar radiation through glazing and the external air temperature were taken as inputs to the model. The derivatives of the model were integrated using a 4th order Runge-Kutta method with 0.1hr step size. As the model was developed for short term dynamics, the initial temperature of the internal room was set equal to the room air temperature at the start of the cooling period. Such an assumption however is invalid for rooms with significant solar gains. Favorable results were obtained by applying the developed model to a high thermal capacity building with the test data taken for a short time period and under both heating and cooling conditions.

Gouda et al [18] simulated thermal behavior of a building along with its heating system using MATLAB / Simulink. The dynamic model developed demonstrated the assistance of solar gain for space heating by adequately designing (passive solar design) the window and shading system. Such a careful design would also avoid unnecessary overheating of the room space in summers. Gouda modeled the room space with a single node diagram and different energy transfer paths as shown in Fig. 2.

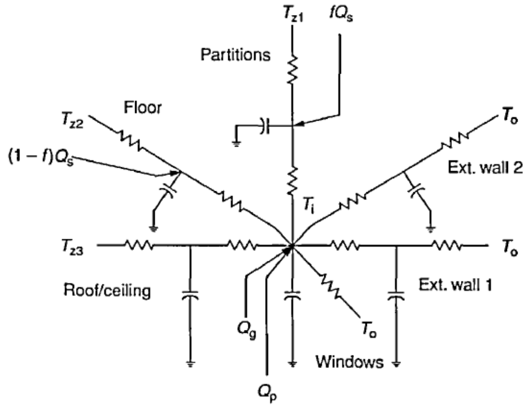

Fig. 2. Building room model of Gouda et al [18]

State space equations of the form X(dot) = AX + BU; Y = CX + DU were developed with X as the state vector consisting of nodal temperatures and U as the input vector consisting of the outdoor temperature, heat gains from the plant, solar heat gain and casual heat gains. An encased finned natural convector was used to model the heating system. A three-port diverting valve that varies the hot water flow rate in response to changes in the room temperature, as measured by a temperature sensor, was used to control the convector. Such a control strategy was called as variable flow-rate constant temperature control strategy. Runge-Kutta scheme available in the solver library of MATLAB was used to solve the non linear differential equations representing the heating system model of the state space building model. Thermo-physical properties of the emitter such as its external and internal area, specific heat, thermal capacity, internal diameter, water flow rate were the input parameters for the heating system model along with a control signal and inlet water temperature as boundary variables. Diffuse and direct solar radiation values from the total horizontal (global) radiation value were estimated by using the model developed by Skartveit and Olseth [19]. Intensity of radiation incident on the surfaces of the building was computed by using diffuse and direct solar radiation values [20]. An overall time constant of approximately 250 hours and of 120 hours under cooling conditions were obtained to achieve free floating response of the room temperature with a 1K unit step excitation of outdoor temperature. The model developed by Gouda et al [18] was investigated for short time scale simulations

Park et al [22] developed a 1R1C lumped parameter network to model heat gain due to home appliances in a well-insulated room. The test room was equipped with a temperature acquisition device and a number of thermocouples, two in the outer side of the room to measure outside air and wall temperature and sixteen inside the room to estimate the indoor temperature. Incandescent lamps, positioned on upper side of walls of the test room, were used as heat sources to identify the global thermal parameters; thermal resistance and thermal capacitance, of the model. The lamps affect to the indoor temperature and electric power consumption of the lamps was converted to the heat flux by heat transfer, i.e. radiation, convection and conduction. From the heat balance equation, indoor temperature in both cases of power source on and off was obtained. And by transient analysis of the thermal network, the value of global thermal resistance was computed. Value of global thermal capacitance was calculated by computing the time constant of the network using least squares method. Simple differential equations were used to represent the nodal temperatures of the model and using these equations the model was developed in MATLAB/Simulink. Simplicity of the model showed different estimations for the value of the thermal capacitance, though simulations showed the trend of the measured data and that of the model as identical. This was due to a large number of assumptions adopted while developing the model. Indoor and outdoor temperatures of the building at initial time instant were assumed to be equal. Internal air temperature of the room, temperature of the equipments in the room and the wall surface temperature were regarded homogeneous. Heat gains through solar radiation, metabolism, infiltration, ventilation and air leakages by window, door, thermal bridges or any small hole were neglected.

A. Model order Reduction

Gouda et al. [8] developed a method for tuning the parameters of a reduced-order lumped parameter model to derive a low-order model to achieve an advantage in terms of computational effort required preserving as much of the dominant dynamic description possessed by the original high-order system as possible. The model involved combining a construction element (external walls, internal partition, door and ceiling) to obtain a 2R1C lumped capacitance model, values of which were computed by a mathematical formula. The developed method was applied to a high thermal capacity example space. In order to yield a most accurate outcome, at least from a modeling point of view, each construction element of the space was split into 20 layers, each layer of equal thickness. A nonlinear multi-variable constrained optimization problem driven by Kuhn-Tucker equations was formulated and applied to minimize the square root of the sum-squared-error between the step responses of the 20th order model and the 2nd order model by varying its R and C parameters. Optimizations were carried out on individual construction elements for unit step disturbances in two excitation variable types: the external temperature and internal surface heat transfer. For a unit step external temperature excitation, both 2nd order and 1st order responses showed appreciable agreements with the benchmarked 20th order model. But for a unit step internal surface heat flux excitation only the 2nd order model showed closeness to the response of the 20th order model giving a poor agreement to the 1st order model. This was due to comparatively, slow charging of the 1st-order model capacitance resulting in a restricted build-up of construction element temperature and, consequentially, limited surface convection back to the space. The quicker charging of the inner capacitance, of the 2nd-order model resulted in a rapid rise in inner material temperature with increased convection and radiation back to the space, resulting in a better tracking of the inner room temperature.

III. FREQUENCY RESPONSE MODELS

Laret [14] developed a simplified dynamic model of a building zone in which doors and windows categorized as light external walls were modeled by a 1R network. Massive external walls of high outdoor side insulation were modeled as a 2R1C network and massive internal walls were modeled by a 1C network to include the mass of the air flowing through the zone under study. The walls of the building under study were categorized as external walls and internal walls. Walls in contact with cold neighbor zones such as car parking etc were regarded as external walls. Temperature profile of such walls was largely influenced by the outdoor temperature. Walls included in the building zone of study like that of floor, ceiling and walls in contact with other rooms like partition walls were regarded as internal walls. Parameters of the model were deduced through indoor temperature response analysis with step inputs of indoor heat flow and outdoor temperature through Laplace transformations. Fourier type boundary conditions were used for external walls and internal walls (for the zone side of the wall). Heat exchange within the walls was related to the wall environment temperature, convection and radiation heat transfer coefficient. Neumann boundary condition was imposed for analyses of internal walls for the null heat flow plane wall side.

Ngendakumana [15] further developed the model proposed by Laret [14] based on the electrical analogy of thermal networks. Masy [16] upgraded the model by adding a specific outdoor branch connected to an outdoor equivalent temperature. Heat transfer due to solar radiation and infra red losses through the roof of the room model was taken into consideration. A series R-C branch was used to model the mass of internal walls included in the building zone model. As the surface temperature on both sides of the internal walls was identical along with surface heat flow signals, there was no transfer of heat across them. The parameters of the walls were tuned using sinusoidal response instead of step response.

All 2R1C network models of the individual walls were then aggregated to construct one single RC model of the building under study. Separate branches were used to represent high mass external walls and for the corresponding high mass internal walls. Admittance matrices of individual walls (both external and internal) were multiplied by their corresponding areas and summed to obtain the zonal admittance matrix. Magnitude and phase measure of the admittance and transmittance figures of zonal walls were equalized for a 24 hours time period. Such an adjustment process resulted in a 2R1C network model for external walls. This procedure was carried out under isothermal boundary conditions. Similar procedure was followed for identifying the parameters of the internal walls model (2R1C) but the adjustment process was carried out under adiabatic boundary conditions. As the R (of 2R1C network model of internal wall) was located on the null heat flow plane side and with no heat passing through the resistor, the R was omitted from the model. 1R network was used to model ventilation heat losses and 1C was used to model the air mass of the building zone. A factor of 5 – 6 was multiplied to the air mass to take into account the lack of homogeneity of the indoor temperature in the zone.

Fraisse et al [9] modeled a multi layer wall using electrical analogy method in TRNSYS. Conduction through the walls was represented with a 3R4C model and the conductive exchanges through windows, convective and long wave radiative heat transfer were modeled using a 1R model. Heat gains through convective heat flows and gains through long wave radiative flows were injected to the air temperature node and the mean radiative temperature node, respectively. Heat gains through solar radiation were injected onto the wall surfaces. The water loop of the heating floor was modeled by 2R1C network. The wall under study was discretized into 100 nodes and was compared to the 3R2C, 3R4C and 1R2C models of the walls by equating the frequency characteristics (amplitude and phase) through spectral analaysis. Several 2R1C models were aggregated to only one 2R1C model and 3R2C model was aggregated to obtain a 3R4C network. A hydraulic heating floor was integrated to the developed analogical building model to limit the problems of convergence during numerical simulations. Two 3R4C models were used to represent the conductive heat transfer occurring above and below the heating film of the heating floor model.

A. *Frequency Domain Regression Models*

Fabric elements of buildings with high mass and a high degree of insulation from outside like concrete or brick walls, etc are rarely in steady state and thus transient analysis of heat transfer through these construction elements is necessary. Wang and Chen [21] calculated the response factors (RF) and conduction transfer functions (CTFs) of building constructions using a frequency domain regression (FDR). The RF and CTF methods, originally yielded using the inverse Laplace transforms, are now used widely for solving the heat conduction equation. Transmission matrix of the multi layer wall is computed by multiplying the transmission matrices of the individual layers which in turn are obtained using the thermophysical properties of the wall layers (thickness, density, thermal conductivity, specific heat capacity). Frequency characteristics of the total transmission matrix within the pre selected frequency range are computed by means of bode plots. These frequency characteristics are complex functions and generally characterized by phase lag (phase angle between peak input and output) and amplitude (ratio of peak output to peak input). An objective function, consisting of frequency dependent weighed errors involved solving a set of linear equations and a polynomial s-transfer function for internal, cross or external heat conduction, respectively was developed. The problem was linear in nature. A step wise procedure to calculate the RFs and CTFs by applying inverse Laplace transforms or Z-transforms on the polynomial s-transfer function was presented. There was no iterative searching for a number of roots of the hyperbolic characteristic equation and thus, the need to find the derivatives of the characteristic equation at the roots and evaluation and summing of the same number of residues was avoided, as was the case in direct root-finding method. The method developed avoided miscalculation due to missing of roots, and the computational process was simple and straightforward. Tests and comparisons for various cases were presented to make the FDR method adequately accurate for the practical applications of engineering and building simulation.

Wang and Xu [11] developed a method to identify the parameters of a simplified building model based on frequency characteristic analysis. Such an analysis involved identifying the parameters of the model using the thermo-physical properties of the building and short term operation data mnonitored.3R2C model was used to simulate the building envelope and the optimal nodal placement of the model was obtained by matching the theoretical frequency response characteristics of the building envelope with the frequency response characteristics of the simplified model using GA estimators. The developed methodology involved computing the theoretical frequency characteristic of heat transfer of the building envelope, followed by deducing the frequency characteristic of the simplified model and then developing an objective function of minimizing the amplitude and phase lag of the theoretical and the simplified model. The optimization involved searching the optimal values of the five parameters of the 3R2C simplified target model allowing the frequency response of the simplified model to best fit the theoretical response. 2R2C network was used to model the building internal mass such as internal structures, partitions, carpet, furniture, etc. The parameters of the 2R2C model were identified with operation data after obtaining the simplified 3R2C models. Windows were modeled as a 1R network. The effect of varying wind velocity on external wall convection coefficients was neglected. Energy consumption of the simplified model was predicted using differential equations and a Runge Kutta algorithm was used to compare it with the measured cooling load.

X. Q. Li et al [32] developed a method to test the accuracy of the CTFs solved through direct root finding (DRF) method, state space (SS) method and the frequency domain regression (FDR) method. Calculation principles of the three methods were implemented on ASHRAE wall 19 and 24 [33]. The method compared the values of heat flux calculated using CTFs with the values obtained using analytical method. Algorithm of the ASHRAE [33] tool kit was used to calculate SS and DRF CTF solutions. The inside and outside film coefficients of the test wall were treated as resistive layers. Inside temperature was regarded as constant. Outside temperature was taken to be of a 24 hour steady periodic profile approximated for 1-hour time steps. Error factors like Fourier number, F_0 and thermal structure factor (S_{ie}) were used as indicators between the fabric elements and CTFs calculations. The thermo physical properties of ASHRAE wall 24 were varied continuously until the CTF solutions fail to converge. When one property of the slab changes proportionally, the other properties were kept unchanged. Whereas for a multilayer ASHRAE wall19, properties of the brick layer and heavyweight concrete layer were varied until the CTF solutions fail to converge. Figure of $1/F_0S_{ie}$ was taken as the wall structure characteristic parameter. Magnitude of error increased with increase in $1/F_0S_{ie}$. Almost 100% error was obtained in case of DRF and SS method but limited error was obtained in case of FDR method of CTFs calculation.

IV. Conclusion

Limited availability of energy and fast depletion of its resources have laid increased urgency to achieve energy efficiency in all sectors. Buildings are one major consumers of energy and thus there is a need to develop effective strategies of energy conservation. This requires constructing an energy model of building under study. This paper presented a brief review of the various techniques that are being used to model the building energy system. Modeling of buildings is not a new concept and has been under research for several years. Numerous models like lumped capacitance models, state space models, frequency domain regression models using conduction transfer functions, thermal response factors have been developed and several works implementing each of the modeling technique has been reviewed. However, to achieve accurate model of a building much more research is required with development of a simple generic model being a mandate.

REFERENCES

[1] F. Bruckmayer, “The equivalent brick wall,” Gesundheuts- Ingenieur 63, 61–65, 1940.

[2] J. Clarke, “Energy Simulation in Building Design,” Adam Hilger, Bristol, 1985.

[3] I. Škrjanc, B. Zupančič, B. Furlan, A. Krainer, “Theoretical and experimental FUZZY modelling of building thermal dynamic response,” Building and Environment, Volume 36, Issue 9, November 2001, Pages 1023-1038, ISSN 0360-1323.

[4] P. Kopeck´y, “Experimental validation of two simplified thermal zone models,” In: Proceedings of the 9th Nordic Symposium on Building Phsyics. Tampere, Finland, 2011.

[5] G. Mustafaraj, J. Chen, G. Lowry, “Development of room temperature and relative humidity linear parametric models for an open office using BMS data,” Energy and Buildings 42,348–356, 2010.

[6] M. Jimenez, H. Madsen, K. Andersen, “Identification of the main thermal characteristics of building components using Matlab,” Building and Environment 43, 170–180, 2008.

[7] G. Mustafaraj, G. Lowry, J. Chen, “Prediction of room temperature and relative humidity by autoregressive linear and nonlinear neural network models for an open office”. Energy and Buildings 43, 1452–1460, 2011.

[8] M. M. Gouda, S. Danaher, C. P. Underwood, "Building thermal model reduction using nonlinear constrained optimization," Building and Environment, vol. 37, pp. 1255-1265, 2002.

[9] G. Fraisse, C. Viardot, O. Lafabrie, G. Achard, “Development of a simplified and accurate building model based on electrical analogy,” Energy and Buildings, Volume 34, Issue 10, November 2002, Pages 1017-1031, ISSN 0378-7788.

[10] G. Hudson, C.P. Underwood, “A simple building modelling procedure for MATLAB/SIMULINK,” Proceedings of the IBPSA Building Simulation ’99 Kyoto, p. 776–83, 1999.

[11] S. Wang and X. Xu, “Simplified building model for transient thermal performance estimation using GA-based parameter identification,” International Journal of Thermal Sciences, Volume 45, Issue 4, Pages 419-432, ISSN 1290-0729, April 2006.

[12] T.L. McKinley and A.G. Alleyne, "Identification of building model parameters and loads using on-site data logs." governing 10, 2008, 3.

[13] S. Bertagnolio, G. Masy, J. Lebrun, P. Andre, "Building and HVAC System simulation with the help of an engineering equation solver," Proceedings of the 3rd National conference of the IBPSA-USA, Berkeley, CA., 2008.

[14] L. Laret, “Contribution au développement de modèles mathématiques du comportement thermique transitoire de structures d’habitation,” PhD thesis, University of Liège, 1981.

[15] P. Ngendakumana, “Modélisation simplifiée du comportement thermique d'un bâtiment et vérification expérimentale,” PhD Thesis in Applied Sciences. University of Liège, 1988.

[16] G. Masy, “Dynamic Simulation on Simplified Building Models and Interaction with Heating Systems,” 7th International Conference on System Simulation in Buildings, Liège, Belgium, 2006.

[17] S.A. Klein and F.L. Alvarado, “EES : Engineering Equation Solver. F-chart software,” 2002.

[18] M.M. Gouda, S. Danaher, and C.P. Underwood, Low-order model for the simulation of a building and its heating system, Building Services Engineering Research and Technology August 2000 21: 199-208, doi:10.1177/014362440002100308.

[19] A. Skartveit and J.A. Olseth, “A model for the diffuse fraction of hourly global radiation,” Solar Energy 38(4) 271-274, 1987.

[20] B.Y.H. Liu and R.C. Jordan, “The long term average performance of flat plate solar energy collectors,” Solar Energy 7(2) 53-73, 1963.

[21] S. Wang and Y. Chen, “Transient heat flow calculation for multilayer constructions using a frequency-domain regression method,” Building and Environment, Volume 38, Issue 1, Pages 45-61, ISSN 0360-1323, , January 2003.

[22] H. Park, M. Ruellan, A. Bouvet, E. Monmasson, R. Bennacer, "Thermal parameter identification of simplified building model with electric appliance," Electrical Power Quality and Utilisation (EPQU), 11th International Conference on , vol., no., pp.1,6, 17-19, Oct. 2011.

[23] M. Vasak, A. Starcic, A. Martincevic, "Model predictive control of heating and cooling in a family house," MIPRO, Proceedings of the 34th International Convention , vol., no., pp.739,743, 23-27, May 2011.

[24] K. Ouyang and F. Haghighat, “A procedure for calculating thermal response factors of multi-layer walls—State space method,” Building and Environment, Volume 26, Issue 2, Pages 173-177, ISSN 0360-1323, 1991.

[25] M. Nowak and A. Urbaniak, "Utilization of intelligent control algorithms for thermal comfort optimization and energy saving," Carpathian Control Conference (ICCC), 2011 12th International , vol., no., pp.270,274, 25-28, May 2011.

[26] M. Nowak and A. Urbaniak, “Computer modelling and simulation of the influence of physical parameters on thermal comfort”, Manuel Feliz Teixeira, J., Carvalho-Brito, A. E., editors, Proc. of The 2005 European Simulation and Modelling Conference EUROSIS-ETI, pp 445-447, Porto, Portugal, 2005.

[27] M. Nowak and A. Urbaniak, “Simulation of integrated control system for climate control”, Sklenar J., Tanguy A., Bertelle C and Fortino G. editors, Proc. Of The 2007 European Simulation and Modelling Conference EUROSIS-ETI, pp 606-610, St.Julians, Malta, 2007.

[28] M. Nowak, “Operating cost optimization of air conditioning systems in the buildings using an intelligent algorithms”, H. Kapron editors, Rynek Energii, nr 3(76) June 2008, pp 48-53, Lublin, Poland, 2008.

[29] M. Nowak and A. Urbaniak, “Optimization of energy comsuption in an intelligent control system of heating and air-conditioning laboratory model”, H. Kapron editors, Rynek Energii, nr 3(88) June 2010, pp 137-142, Lublin, Poland, 2010.

[30] M. Nowak and A. Urbaniak, “Predictive control for thermal comfort optimization and energy saving”, G. K. Janssens, K. Ramaekers, A. Caris editors, Modelling and Simulation 2010, Pub. EUROSISETI, pp 421-425, Ostend, Belgium, 2010.

[31] M. Nowak and A. Urbaniak, “Utilization of intelligent HMI/SCADA system in environmental engineering”, A. K. Varga, J. Vasarhelyi editors, Proceedings of 11th International Carpathian Control Conference ICCC’2010, Pub. Department of Automation University of Miskolc, pp 83-86, Eger, Hungary, 2010.

[32] X.Q. Li, Y. Chen, J.D. Spitler, D. Fisher, “Applicability of calculation methods for conduction transfer function of building constructions,” International Journal of Thermal Sciences, Volume 48, Issue 7, Pages 1441-1451, ISSN 1290-0729, July 2009.

[33] ASHRAE, “ASHRAE Handbook of Fundamentals,” American Society of Heating, Refrigerating, and Air Conditioning Engineering, Inc., 2001.